Nanostructures in Polymer Matrices

A Report on a Workshop organised by the University of Nottingham and sponsored by US Army European Research Office, London, UK

September 2001

Editors
Christopher D Rudd, University of Nottingham
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Abstract

An ERO sponsored Workshop on **Nano Structures in Polymer Matrices** was held in order to establish the status of international science and technology and to develop recommendations for basic research. This addressed both theoretical (modelling) and experimental techniques to develop and understand these materials. The Workshop was held at Risley Hall, Derby, UK. Twenty invited participants, comprising a mix of scientists and engineers with complementary expertise met in an intensive fashion over 2.5 days with a series of timetabled presentation and discussion events. The participants were requested to address a series of specific questions intended to provoke constructive recommendations for future research strategy in this area. These responses are included within the report, along with supporting background information on the participants and their presentations. Further information on the workshop, including downloadable presentations is available at: http://www.nottingham.ac.uk/~eazwww/composite/nanostructures2001

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1. Introduction

Background

Modification of polymer matrix composites by nanostructures may provide materials tailored to functional requirements. Nano-scale materials have become available for incorporation in structural materials during the past decade. Early work indicates that they do confer significantly improved properties (not incremental improvements). Examples include toughening of polymer composites by nano-scale metal oxide particles as shown by the US Natick Soldier Center. Centres of expertise in several countries are springing up.   For instance, studies are now being carried out at government laboratories and universities including Clarkson and Penn State in the U.S., Cambridge in the U.K., Freiburg in Germany, the University of Bordeaux in France, and the Twente University in the Netherlands.   Claims of big increases in tensile strength properties and inter-laminar fracture toughness have been made.   Fundamental understanding of interactions between nano-scale structures and polymer matrices will enable modelling and design of structures for desired properties, improved maintenance, and estimation of lifetimes. However, it remains unclear at this time what controls the mechanisms of stiffening or strengthening and, particularly, what limitations exist on property improvements.

Relevance

These new structures will be cheaper, lighter, stronger, easier to maintain, with predictable modes of failure.   The possible areas of application include personal protection, armour, load carriage, helicopter rotors, soldier uniform and headgear.

Workshop Objectives

- To review current evidence for the use of nano-scale materials (particles and fibres) in polymer composites and advantages conferred.

- To focus on hardness/strength/ toughness as primary concerns but also explore flexibility, resistance to fatigue, and chemical resistance.

- To explore the use of nano-scale materials as actuators for smart materials.

2. Summary of Conclusions and Recommendations for Research

Mechanical Performance

- There is clear evidence that nano-composites offer significant performance improvements over their base polymers. Depending on the materials combination, most of the static properties may be improved. Perhaps the most interesting benefits are to elastic modulus and compression strength. There is little evidence to suggest that these materials have potential (in isolation) for enhancement of toughness or ballistic performance.

Functional Performance

- Improvements in functional properties probably provide the main driver for nano-composites research and for new applications. Most new research in the field is headed in this direction. Spectacular improvements in barrier properties, conductivity, flammability and thermal stability have all been noted and these features are beginning to be exploited commercially.

Materials Selection and Availability

- A wide range of polymers can be incorporated into nano-composites but feasibility and economics tend to limit the types of nano-reinforcement with which they may be combined successfully. The main nano-reinforcements of interest are clay-derived silicates and carbon nano-tubes. The main potential for layered silicates seems to be with thermoplastics and the most mature system here is montmorillonite with polyamide 6. However, aggressive developments within the materials supply base mean that other combinations based on e.g. polyolefins will be available in volume before long. Laboratory routes exist for synthesising nano-composites from huge variety of polymer types and it really remains for a sound commercial case to exist for volume-capable processes to be established. Similarly in the case of carbon nanotubes; the supply base is immature but considerable potential exists for using these materials in smart applications, circuitry or other circumstances where conductance is important.

Nano-composites and Long Fibre Composites

- While there remains serious doubt over the potential of nano-composites to match the structural properties of high performance metals or long-fibre composites there may be useful mileage in combining nano and long-fibre technologies. Here, the nano-reinforced matrix may add value to the material by e.g. improving compression strength, dimensional stability, environmental resistance or functional properties. One immediate prospect is to dampen out the anisotropic conduction in conventional graphite-epoxy.

Manufacturing

- The manufacturing environment for nanocomposites is relatively immature and this assertion applies to both raw materials and the nano-composites themselves. Limitations on quantity and quality (at a realistic cost) of raw materials are inhibiting progress and industrialisation of nano-composites fabrication is patchy. Many of the promising nanocomposite combinations are problematic to fabricate and there is an incomplete understanding of the factors controlling e.g. platelet dispersion with layered silicates and the subsequent mechanical response.

Applications

- Near term applications are essentially modified polymers where e.g. the introduction of a nano-filler to replace clay tactoids provides enhanced transparency or barrier properties. Similarly, small additions of carbon nanotubes may be incorporated into a commodity polymer to provide electrical conductivity. In the medium term it is expected that these and other functional attributes (e.g. fire retardancy) will be exploited very widely and that nano-composites will be used to add value to a huge variety of polymer and polymer composites applications – these will be limited only by their cost base. In the long term, given manufacturing developments and improvements in fundamental understanding of mechanical behaviour, structural and "smart" applications of carbon nanotubes that exploit their unique performance are feasible.

Probes

- The absence of a single, convenient technique for mapping nano-composite structures is a current drag factor. For layered silicates, this translates to the identification of polymer within galleries, the level of interfacial adhesion and the orientation and distribution of platelets. A variety of characterisation techniques are used at present but little improvement over X-ray diffraction and transmission electron microscopy is evident. Local measurements may be misleading and are subject to misinterpretation. New techniques are required.

Fundamental Understanding and Modelling

- Generally speaking, the understanding of nano-composite formation and behaviour is not sufficiently advanced that satisfactory models (rather than molecular simulations) may be abstracted. Clearly, this inhibits any reliable predictions of macro-scale properties.

R&D Planning

- Perhaps the most urgent need is for fundamental understanding of materials interactions at the nano-metre scale. This requires developments in both characterisation and modelling techniques.

- Manufacturing developments are necessary for progress with raw materials and composites fabrication.

- Applications research is likely to pay greater dividends where focused on exploiting functional properties and synergy with other materials.

Exploitable Features of Nanocomposites
- low oxygen permeability
- low heat release rate
- thermal stability
- high transparency
- low coefficient of linear thermal expansion
- modulus improvement
- conductive polymers

Scientific and Technical Issues
- limited understanding of dominant mechanisms
- ceiling on property improvements
- unreliable or time-consuming characterisation techniques
- no reliable property models
- uncertain influences of processing
- high raw materials costs
- immature supply base

3. Workshop Presentations

Chairmens' Remarks

Co-chairmen Chris Rudd and Bob Shaw opened the workshop by reminding the participants of the thrust of the meeting and the questions that they had been asked to consider in advance (these also provided the framework for syndicate discussion periods):

1. What is the current evidence that nanostructures provide useful properties? What is the significance of scale?

2. How can we probe into the interfaces among the structures and the polymer matrix? What experimental tools now exist that are likely to be most useful? If you could invent a better tool, what would it do?

3. How can we calculate the interface properties? Do proper models exist? Are they phenomenological or do they reflect some fundamental understanding? Are current computational facilities adequate?

4. How can we ensure a balance among basic research and the other steps in the chain to manufacturability? It would be foolish to spend a lot of research on a material that will be too expensive to make (unless it teaches other lessons). On the other hand, expensive materials often become cheap. Nevertheless, one ought to be able to proceed sensibly.

5. What are the most promising nanostructures and matrices - for strength, other enhanced (or new) properties?

Speaker abstracts were collected in advance and are reproduced in the following section. The talks were grouped loosely in the following technical areas:

- Polymer composites with nanoparticles
- Strength and fracture
- Modelling
- Adhesion
- Manufacturing
- Functional materials - beyond strength

During the workshop, electronic copy was provided by the speakers and the individual presentations can be downloaded from :
http://www.nottingham.ac.uk/~eazwww/composite/nanostructures2001

The European Research Office: Organization, Operation, Interests in Nano-Materials

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The European Research Office seeks to develop cooperative projects among US Army and European* scientists and engineers. ERO belongs to the Army Research Laboratory which, along with the Medical Command and the Corps of Engineers, has the responsibility for performing most of the Army's basic and applied research. ERO uses four principal methods: 1. arrangement and support of expert travel between the US and Europe, 2. support (and, in some cases, initiation) of conferences and workshops focused on an area of Army interest, 3. support of research projects performed in Europe, 4. oversight for Army customers of (generally large) projects requiring special European expertise and/or facilities.

Currently the US DOD supports and performs considerable work in nano-science. Programs include the "Defense University Research Initiative in Nano-Technology" (DURINT) with fifteen multi-disciplinary centers.   Among center focus areas are bio-technology, electronic and structural materials, quantum devices, and polymer composites. In 2002, the Army is expected to establish a major university center on "Nano-science for the Soldier". An Army committee assisting in developing plans for this center have recommended research to develop materials with high strength and light weight; capabilities for camouflage, laser protection, power distribution, and selective permeability; and materials with embedded actuators.

Current nano-material projects at the Army Research Laboratory include:

- Hybrid organic/inorganic polymer matrix nanocomposites for transparent armor, protective soldier clothing, lightweight ballistic protection, wear-resistant coatings.
- Nano-particulate boron carbide monoliths and composites for armor.Polymer/polymer multi-layers for transparent armor, ballistic protection, packaging, and optical applications.Perm-selective polymer membranes for fuel cells and soldier protective clothing.Processing polymer nano-fibers for nuclear/chemical/biological defense: vehicular filtration systems, protective clothing, personnel armor.

We planned this workshop to:

- Assess the current state of research on nano-structures in polymer composites and to map out the most promising paths forward.
- Demonstrate US DOD interests in polymer composite research to European scientists.
- Develop recommendations for investment in research on polymer composites.

*ERO responsibility extends beyond Europe. This talk was addressed to European scientists only.

Nanocomposite Materials for Future Warrior Systems

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The Natick Soldier Center is conducting research both in-house and extramurally into new materials based on nanotechnology. These materials are primarily, but not exclusively, polymer matrix composites. The advantage of these materials is that they allow one to get around some traditional materials tradeoffs. For example, improving both strength and toughness. An important area of application for Future Warrior Systems is ballistic protection. Additionally of interest are multifunctional materials, where nanometer scale particles can impart properties such as flame resistance or electronic properties without degrading other physical properties such as durability or ease of manufacture. The difficulty, which comes with these new materials design possibilities, is that the design rules are not well understood. The more unexpected and dramatically different the

properties of these new materials are the more unlikely that those properties can be predicted a priori. Preliminary results of the Natick Soldier Center materials nanotechnology program will be presented as well as some results from other groups, which suggest that new materials based on nanotechnology offer the prospect for new materials with dramatic improvements in properties for Future Warrior Systems.

Nanostructured Polymeric Materials for Space and Aerospace Applications

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Unquestionably, nanostructured materials and their applications will lead to a materials revolution, propelling even greater innovation of aircraft and space systems as well as generating new commercial products. Over the last decade, the utility of nanoparticles as additives to enhance polymer performance has been established. Not withstanding these accomplishments, an understanding of the fundamental correlation between nano (1-100 nm) and mesoscale (100-1000 nm) structure and ultimate physical, mechanical and thermal properties have only been tentatively examined for a few specific systems, without the possibility for any broad predictive guidelines being discernible. As with other multiphase systems exhibiting nano (1-100 nm) and meso (100-500 nm) order (such as biopolymers, block-copolymers, colloidal suspensions, liquid crystals), physical properties ranging from toughness to optical clarity are determined by morphology on various length scales which in turn is dependent on everything from process history to specific polymer-nanofiller interactions. Additionally, because of the morphological length scales, the exceedingly large interfacial area between constituents results in the volume fraction of interfacial regions approaching one. Thus physical properties are dominated by the properties of these interfacial regions and understanding chain behaviour (conformation, relaxation, crystallization) in these regions is paramount to understanding these nanocomposites.

Nanotechnology and nanostructured materials research are a pervasive technology simultaneously encompassing many fields of study. Currently, numerous multi-disciplinary internal and external efforts in the areas of nanotechnology and nanostructured materials are ongoing at the Air Force Research Laboratory, Materials and Manufacturing Directorate (AFRL/ML). By combining traditional material approaches (such as synthesis, processing, morphological evaluation and extensive electronic, optical, thermal and mechanical characterization) with cutting-edge innovation and developments in nanoscale surface science, colloidal science, computational techniques, and biology, revolutionary advances in hybrid (multi-component) material systems with exquisite structural control simultaneously on a spectrum of length scales (macroscopic to the nanoscopic) are under development. These efforts will impact all aspects of aerospace systems including multi-functional structural components, smart coatings, filters and additives, multimode sensors and ultra fast data acquisition/storage/ processing/transmission systems. This presentation will provide an overview of various nano-material research thrusts in the polymer branch.

Damping across the Length Scales

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Energy dissipation (damping) in structures/materials is important as it reduces resonant amplitudes/noise levels giving enhanced integrity and life cycle behaviour. If it is possible to add external damping treatments then it is possible to create significant amounts of damping. This is macro scale damping. If one has to rely on the inherent microstructure the damping levels are much smaller, this brings us to the microscale. If we go to the nanoscale, the damping levels may be smaller still. However, by invoking the properties of nano-auxetics/nanostructures it may be possible to control the wave propagation in the material and enhance the energy dissipation. The presentation considers these aspects and discusses whether nanoscale technology can assist in improving the inherent damping of materials.

Development of Polymer Nanocomposites by Reactive Extrusion

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Polymer-layered mineral nanocomposites are considered as a new class of advanced organic-inorganic materials, not only on account of their potential technological applications, but also for providing suitable systems in view of the investigation of fundamental scientific issues concerning confined polymers. The study of the formation, structure and dynamics of nanocomposites can lead to a better understanding of the behaviour of organic-inorganic hybrids, and of polymers in a confined environment or at a solid interface.

Thermoplastic polymers filled with nano-layered minerals are appropriate systems for the formation of intercalated or delaminated nanocomposites. Intercalated polymer nanocomposites consist of polymer chains inserted between the inorganic layers, resulting in a well-ordered, stacked multilayer structure with a repeating spacing of a few nanometers. Delaminated or exfoliated nanocomposites contain individual inorganic layers (ca. 1 nm thickness and 100-1000 nm in lateral dimensions) homogeneously dispersed in the polymer matrix, with high aspect ratios, comparable to those found for short -fibre reinforced polymers.

The many useful properties of polymers such as mechanical properties (modulus, strength, toughness and impact resistance), chemical inertness, gas permeability resistance, thermal stability and melt-processability, can be built into new materials via nanocomposites with thermoplastic polymers. The enhanced properties are mainly ascribed to the nanoscale morphology of these composite materials.

Recently, the MSC-Blend Research Group has been involved in dispersing layered silicates in a polystyrene and a polycaprolactone matrix on a nanometer scale. These nanocomposites were obtained by monomer intercalation between the silicate layers followed by in-situ polymerisation using reactive extrusion.

Another very attractive method for preparing polymer nanocomposites is the melt intercalation approach. It consists of inserting the thermoplastic polymer melt into the interlayer space of the mineral layers to form ordered nanocomposites. Interestingly, these nanostructured materials can be prepared by using conventional melt-processing techniques such as extrusion.

The performance improvements of thermoplastic polymer nanocomposites depend to a large extent on the distribution and arrangement of the mineral layers as a result of intercalation and/or exfoliation, and on the interfacial bonding between the mineral layers and the thermoplastic polymer.

Layered minerals are hydrophilic and most polymers are hydrophobic. To enhance the mineral-polymer interaction, pre-intercalating long chain alkyl ammonium ions as surfactant can modify the mineral, so that it becomes organophillic. Depending on the interaction between the layered silicates and the nature of the surfactant, different types of nanocomposites ranging from intercalated to exfoliated can be elaborated. It was shown, recently, that using appropriate premade block or graft copolymers as compatibilising agent can also improve the interfacial interaction between the matrix polymer and the layered mineral. Block or graft copolymers having one sequence that is chemically identical or completely miscible with the matrix polymer, and another sequence that is compatible with the mineral, are applied to lower the surface energy of the layered inorganic material and to improve the wetting characteristics with the polymer.

Another novel strategy to improve the mineral-polymer adhesion would consist in forming in-situ a block or graft copolymer during melt-processing, also acting as a potential interfacial agent. Block or graft copolymers with various block lengths may be formed in-situ as a result of chemical reactions between the functional groups belonging to the matrix polymer component and the alkyl cations of the surfactant. In addition, the exchange reactions will occur at the organic/mineral interface, allowing to improve the adhesion between the polymer and the inorganic layers.

The main goal of our research program is to prepare nanocomposite materials based on thermoplastic polymers and clay by reactive melt-extrusion, using a two step procedure. In a first step the swelling of the silicate layers of clay will be performed via an exchange process of the cations located between the crystalline layers against organic onium type cations. These organic cations are required to have another functional group in order to be able to react in a subsequent step with the matrix polymer during melt-processing in an extruder. This will finally lead to a separation of the layered silicate into single nano-platelets and/or small clusters of nano-platelets, and their homogeneous dispersion within the polymer matrix.

This study is also focused on the nanophase morphology development during the extrusion process, and on the nucleation and crystallization behaviour of the polymer matrix as affected by the nanomorphology during cooling for the melt.

The ultimate mechanical and dynamic mechanical properties are investigated in correlation with the nanophase morphology, interfacial adhesion and semicrystalline structure of the polymer matrix.

Nanostructures in Polymer Matrices: A US Navy Perspective

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This paper will review basic and applied research performed at the US Naval Research Laboratory in polymer composite materials. Research work done on high temperature polymer composites will be highlighted. These materials are designed to withstand temperatures exceeding 700°C. Efforts are under way to include nanoparticulates into polymer structures to improve strength as well to design adaptive, functional or smart structures. Two processing routes are being explored. One involves mixing nanomaterials and polymer materials. The other involves *in situ* formation of nanoparticles from organometallic precursors. The Navy is also interested in exploring the embedding of nanostructured devices such as nano-sensors to monitor the performance and health of aerospace polymer-matrix structures. On this topic, possible areas of research and issues will be presented.

Compressive strength of fibre composites

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The compressive strength of unidirectional fibre composites is usually lower than can be expected on the basis of the compressive strength of the fibres. This is caused by the fact that fibres can bend and break due to a lack of support by the matrix. Depending on the failure mechanism the limiting property of the matrix material is the yield stress or the shear modulus. Both the modulus and the yield stress can be increased by the addition of a small amount of high aspect-ratio nanofiller, like exfoliated clay or mica. The morphology, the mechanical and the rheological properties of these nanocomposites will be investigated to understand their possibilities as matrix materials in unidirectional fibre composites. Fibre composites with filled thermoplastic and thermosetting polymers will be made and the compressive properties will be tested for different matrix compositions. On the poster the first results will be showed of the moduli, the yield stresses and the rheological properties of some nanocomposite matrix materials.

Morphological Behaviour of Model Polymer-Layered Silicate Nanocomposites

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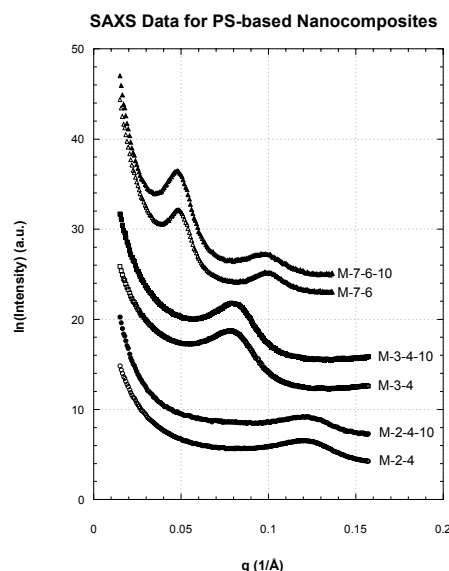
Polymer-layered silicate nanocomposites have been a focus of great interest over the last decade or so due to significant improvements in mechanical and thermal properties reported by researchers at Toyota for nylon-6 based materials. During this time, a significant effort has been focused on research having as its goal the fabrication of nanocomposites with the most beneficial morphology, an exfoliated morphology, by direct processing and synthesis methods. These methods include *in situ* polymerisation of monomer, solution processing of clay and polymer in a co-solvent, and melt mixing by mechanical processing techniques. These techniques place restrictions on candidate materials for nanocomposites, reducing the engineer's ability to incorporate layered silicate clays in systems of specific interest. Additionally, little work has been directed at a methodical understanding of the basic underlying thermodynamic driving forces between the components in PLS nanocomposites, which govern equilibrium behaviour.

Recent research at the Army Research Laboratory and the University of Delaware seeks to examine these basic relationships between silicate, surfactant modifier, and homopolymer matrix, based on the theoretical predictions of Balazs, Singh, and Zhulina. As a first step, the morphological behaviour of a model system based on polystyrene and montmorillonite has been examined according roughly to the specified conditions in the Balazs model. For this work, model PS-based surfactants with low polydispersities and trimethylamine cationic end groups were synthesized. After standardizing the modification procedure, cleaned montmorillonite was modified to high levels of coverage with each of 5 surfactants. The modified clays were then mixed with PS homopolymer 95 repeat units long, and annealed for a week at 125ºC. This processes was hoped to allow an equilibrium morphology to be formed without the addition of any shear forces, such as in twin-screw extrusion of commercial nanocomposites. The modified clays and the nanocomposites were then characterized by TGA and SAXS.

The SAXS data conclusively show that, while modification with surfactant was successful, no intercalation of the PS homopolymer occurred during annealing. This result is attributed to autophobic dewetting-type behaviour, resulting from having dense polymer brushes on the silicate surfaces. While the Balazs model predicts that generally having longer surfactants should aid the intercalation process by returning conformational entropy to the confined homopolymer, further examination reveals that for dense brushes, the model reflects the observed autophobic dewetting behaviour.

Work currently underway on this system seeks to address the issues raised by these results. First, lower surfactant coverages are to be examined. The Balazs model uses a coverage of 0.04 cations/lattice unit, which corresponds roughly to the very low coverage of one cation per 12 nm^2. This specific level of coverage is to be targeted. One issue that may complicate this experiment is that the Balazs model neglects the repulsive enthalpic interactions between the hydrophilic layered silicate surface and the hydrophobic homopolymer matrix. Therefore, work is also underway to investigate the behaviour of systems with mixtures of surfactants modifying the silicate surfaces, in which longer chains will provide entropic benefits, while shorted chains screen unfavourable enthalpic interactions.

Figure 1. SAXS data for modified clays and their corresponding PLS nanocomposites, for three model surfactants and PS homopolymer matrix.

In conclusion, it is hoped that this basic research effort will provide valuable insight into the equilibrium behaviour of polymer-layered silicate nanocomposite materials. Where as currently,

empirical efforts based on limiting fabrication techniques such as in situ polymerisation dominate the research into new nanocomposite materials, the goal of this work is to allow the fabrication of PLS nanocomposites from existing polymers with specific, well defined properties.

Nanostructures and materials function – the ARL program

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Property enhancements (e.g., decreased gas/liquid permeability and moisture uptake and increased fire/flame resistance, heat distortion temperature, strength and stiffness) of polymer layered-silicate (PLS) nanocomposites relative to conventional mineral-filled polymers are attributed to the nanometer length scale and high aspect-ratio characteristics of the individual clay (or nanoclay) platelets. The polymer matrix material, processing conditions, nanoclay microstructure and surface chemistry, as well as the dispersion and extent of exfoliation of the nanoclay, have a profound effect on the physical and mechanical properties of PLS nano-composites. Sometimes, the effects may be detrimental to desired engineering properties such as fracture resistance or impact behaviour under high-strain rate conditions. For example, polycarbonate (PC) has outstanding ballistic impact strength and good optical clarity, but relatively poor UV stability, abrasion and solvent resistance). Incorporation of an organo-modified nanoclay to improve the environmental durability of PC also increases the polymer's tensile modulus and yield strength, but dramatically reduces ductility. PC/PLS nano-composites with 5% nanoclay exhibit a brittle mode of failure upon tensile loading and ballistic impact. On the other hand, PC/PLS nanocomposites with 2.5% nanoclay display similar but slightly decreased ductility compared to the PC-control. Shear yielding with formation of a stable neck profile upon tensile loading is the predominant failure mechanism in PC; however crazing occurs in the PC/PLS nanocomposites. This is attributed to an increase in yield strength, which may suppress yielding and favour craze formation. PC/PLS nanocomposites with 2.5% nanoclay exhibit a mixed mode of failure that is consistent regardless of quasi-static tensile, flexural or dynamic impact loading conditions. Good particle distribution and proper interfacial bonding facilitate stress transfer between the matrix and the intercalated layered-silicates and result in an overall improvement in mechanical properties. Currently, our research is focused on determining the critical material parameters that affect the mode of failure of PC/PLS nanocomposites encountered under various loading conditions. We are particularly interested in understanding the high-strain rate behaviour of PC/PLS and other types of nanocomposites and how their performance under ballistic impact conditions might be improved.

Our recent work on the design of transparent armour indicates that hybrid hard/ductile layered polymers are the materials of choice for achieving armour systems with lightweight and better impact strength. For example, transparent armour consisting of a brittle thick-PMMA (polymethylmethacrylate) front layer and a ductile thin-PC back layer exhibits significantly improved ballistic performance compared to either of the monolithic components of equivalent thickness. Preliminary studies incorporating PC/PLS nanocomposites as the front layer with a ductile PC back layer clearly demonstrate that the hybrid layered polymer armour system has much better ballistic impact performance than either the PC/PLS nanocomposite or the PC of equivalent thickness. Experimental results will be presented and ideas for optimising the impact properties of hybrid nanocomposite armour materials will be discussed.

Nanocomposites in polymer matrices: manufacturing issues

Chris Rudd, Professor of Mechanical Engineering, School of Mechanical, Materials, Manufacturing Engineering and Management, University of Nottingham, University Park, Nottingham NG7 2RD

Polymer matrix composites as engineering materials have a history of around half a century which is marked by a series of key enabling developments in materials. These new materials only become established in real world applications when the corresponding conversion techniques become available. The economics associated with conversion also dictates the range of applications. This talk will review the nanocomposites developments from the perspective of manufacturing long fibre

composites. We shall attempt to identify where nanocomposites fit within the existing materials families in the context of cost and performance. We shall examine the potential for making long fibre composites with nano-reinforced thermoset and thermoplastic matrix materials and examine the structural possibilities and potential usage areas together with the likely drivers for new applications. Finally, we will chart the level of known activity in the UK and attempt to identify opportunities to capitalize on recent developments.

Modelling Bone as a Natural Hybrid Nanocomposite

David Porter, Structural Materials Centre, DERA Farnborough A7/2008, Farnborough GU14 0LX

Bone is considered as a model structural material which is a natural polymer-inorganic hybrid nanocomposite, with the added complication of having highly anisotropic inorganic particles distributed within the polymer matrix. The objective of the modelling is to understand how particle dimensions on a nanometer scale can give advantages in structural properties to a composite. This understanding should then facilitate the design of synthetic nanocomposites with improved engineering performance. Such materials would have an improved balance of stiffness and fracture toughness and durability, but with the added advantage of high damping of shock and vibrations.

The key step in the model is to quantify the effect of energy exchanges at an atomic/molecular level between materials at an interface; both the magnitude of these effects on mechanical properties and the spatial extent of the interaction around each interface. This step allows a composite material to be modelled as having three components: the two individual materials and the interface zone between them. The nanocomposite can thus be modelled by means of continuum-level anisotropic composite theories (such as Halpin-Tsai), but to include the detailed atomic level information about interfaces.

Models for the individual properties of hydrated collagen and hydroxyapatite are presented which use a self-consistent set of structural parameters for both material types. This allows the sharing of energy at interfaces to be expressed as a simple analytical formula as a function of distance from an interface. We see that energy sharing occurs over a distance of less than 10 atomic layers from an interface, but these distances are significant on a scale of nanometers, such that interfaces may dominate the properties of a nanocomposite.

Predicted material properties are used in an anisotropic composite model to predict the elastic modulus and fracture of bone as a function of mineral volume fraction. Predicted mechanical and fracture properties are shown to be in agreement with experimental observation.

The model for bone provides some very interesting insights into a mechanism for the mechanism for nanocomposites and explains why nanoscale dimensions are important in a composite. However, some material disadvantages of a bone-like nanocomposite are suggested by the model, such as a very limited temperature range for an optimum combination of properties.

Mechanical Properties of Particulate-Modified and Nanocomposite Thermoset Polymers

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Introduction
Particles have been used extensively to modify the properties of engineering polymers, although recently the emphasis has shifted from the use of particles as fillers to their use as functional materials, and in particular towards the formation of nanocomposites. The present work will investigate the effect that the addition of particles has upon the mechanical properties of polymers, and discuss whether the formation of nanocomposites gives a greater increase in properties than the

formation of conventional micro composite materials. The properties that are discussed most frequently in the literature are modulus and tensile strength. However, other properties will be affected by the addition of particles, including the fracture toughness, the water or solvent uptake (i.e. barrier properties), and the fire resistance. This paper will concentrate on thermoset polymers, although some thermoplastics will also be discussed as there is generally more data available for these systems. The thermoset polymers most commonly used for the formation of nanocomposites have been epoxies, but some acrylics and cyanate esters have also been used.

Modifiers

A range of particles have been used to form micro- and nanocomposites, and this work will concentrate on preformed and inorganic particles rather than polymeric modifiers (e.g. polyethersulphone and rubber). The particles used include glass, silicon carbide, aluminium boride, carbon and boron fibres, steel, silica and carbon nanotubes, mica, tetraethoxysilane (TEOS) and layered silicates (clay). Three-dimensional silicate networks have also been formed, with the polymer phase filling the channels within the network. Nanocomposites formed from epoxy plus polyhedral oligomeric silsesquioxane (POSS) have also been studied.

Production of Composites

Thermoset micro- and nanocomposites are produced using in-situ polymerisation. The monomer is mixed with the modifier, and polymerised. In some cases the modifier is surface-treated prior to mixing.   The production of polymer-layered silicate nanocomposites has generally used alkylammonium-exchanged clays. Depending on the length of alkylammonium chain, amongst other factors, an exfoliated or intercalated nanocomposite, or a micro composite is produced. Hence varying the surface treatment can produce a range of structures. However, to produce good materials it is necessary to overcome the problems of particle aggregation associated with the use of layered silicates in the past, that led to poor mechanical properties.

Note that many of the modifiers used are naturally-occurring materials, and the aspect ratio of the particles will vary due to the irregular particle shape. However, the generally-accepted definition of aspect ratio is the average diameter divided by the average thickness.

Modulus

Unmodified thermoset polymers have Young's moduli of about 2 to 4 GPa. The addition of inorganic particles will increase this value, as the inorganic materials have higher moduli (the modulus of mica is 170 GPa). There are a number of models available to predict the modulus of particle-modified composites. These include models by Halpin, Cox, Nielsen Christensen and Manera, plus the rule of mixtures. The rule of mixtures gives an upper-bound value for the predicted modulus, whereas the other models agree more closely with the experimental data. These models show that the particle aspect ratio and the particle/matrix adhesion have the greatest effect on the composite modulus. High aspect ratios and good particle/matrix adhesion are beneficial. The particle shape, whether spherical, rod-like or plate-like, affects the modulus, although most of the predicted moduli are independent of the particle size.

The moduli of polymer-silicate nanocomposites have also been shown to be greater than those of the unmodified polymers . For example, the modulus of epoxy can be almost doubled by the addition of 10% by weight of surface-treated silicate. As above, higher aspect ratios lead to higher moduli. Similarly, exfoliated silicate platelets give a higher modulus than an intercalated structure, due to the higher aspect ratio. The measured moduli are rarely compared to the theoretical models discussed above, but when comparisons are made the data agree fairly well. The formation of polymer-silicate nanocomposites has also been shown to increase the measured glass transition temperature, T_g, as well as the modulus of selected thermoplastics. Hence as well as increasing the modulus at ambient temperature, the maximum service temperature of the material is increased.

The addition of carbon nanotubes also increases the polymer modulus. Using 5% by weight of multi-walled carbon nanotubes increased the modulus of epoxy from 3.1 to 3.7 GPa in tension, and from 3.6 to 4.5 GPa in compression. This is a small increase considering the nanotube modulus is extremely high, approximately 1000 GPa. The low composite modulus is probably due to poor

adhesion between the matrix and the tubes, or slippage of one tube inside another within the multi-walled structure.

Tensile Strength

Conventional theory says that the addition of particles will increase the tensile strength of a material, although experimental results generally indicate a decrease. The reason for this discrepancy is that the theoretical models do not take into account the ability of the particles to act as defects which can initiate failure. Further, there is a greater stress-concentration effect for platelet-reinforced materials than for those with fibre reinforcement. Hence a lower tensile strength would be expected for platelet-modified than for fibre-modified composites. The models do, however, show that the tensile strength is dependent upon the adhesion between the particles and the matrix. Good adhesion results in the greatest increases in tensile strength. Glavinchevski and Piggott produced polycarbonate specimens reinforced with 20 mm diameter steel discs, and showed there was no effect of aspect ratio (in the range 100 to 800) or of particle shape on the tensile strength.

Some models, for example the Nielsen model, predict that the tensile strength of particle-filled composites is only higher than that of the pure polymer when the volume fraction of particles is greater a limiting value (0.39 for the Nielsen model). However, increases in tensile strength have been reported for nanocomposite materials at much smaller volume fractions. Improvements have been seen for epoxy-silicate nanocomposites using elastomeric epoxies with up to 23% by weight of silicate. However, no increase in tensile strength has been reported when the T_g of the matrix is high.

Fracture Toughness

As discussed above, the particles can act as a site for the initiation of failure. However, during fracture the particles will interfere with the crack, and increase the measured fracture toughness. Faber and Evans proposed a model to predict the toughening effect of particles using a crack deflection model. When an advancing crack encounters a particle, there is an initial deflection of the crack which tilts the crack out of its advancing plane. Subsequent twisting and tilting of the crack occurs as the deflected crack encounters further particles, and the deflected crack is subjected to mixed-mode loading. The tilted crack experiences mode I (tensile) and mode II (in-plane shear) loading, while the twisted crack experiences mode I and mode III (anti-plane shear) loading. It is well-known that fracture under mode II and mode III loading requires more energy than in mode I, and hence the local mode-mix increases the measured fracture energy in a nominally mode I fracture test. Kinloch and Taylor have shown increases of fracture energy, G_c, of up to 100% in a micro composite using 10% by weight of mica. The particles were observed to initiate plastic hole growth in the matrix, hence increasing the toughness. However, they expect even larger increases if the platelets were more randomly oriented, as predicted by the Faber and Evans theory. Epoxy-silicate nanocomposites can also give increases in fracture toughness, K_c, of almost 100%.

Lourie et al observed that damage in carbon nanotube occurred in a similar manner to that in carbon fibre composites, and could be described by conventional stress-transfer models, e.g. the Kelly-Tyson model. During fracture the nanotubes bridge across the fracture surfaces behind the crack tip, and will increase the measured fracture toughness by a process of stretching and debonding.

There is a paucity of data available for the impact strength of micro- and nanocomposites. However, Maine reports that the impact strength of mica-modified polymers, measured using notched and un-notched Izod tests, has been found to be low, and is considered to be a function of the platelet size.

Water and Solvent Absorption

The formation of epoxy-silicate nanocomposites has been shown to reduce the rate of solvent uptake. The reduction in the rate of uptake has been described using a tortuous path model, where the water or solvent must diffuse further because it must go around the platelets (assuming that the platelets are oriented perpendicular to the overall diffusion path). As the diffusion path is longer, the diffusion rate is reduced. However, water diffusion rates for nanocomposites that are forty times less than those of the unmodified polymer have been observed by Beall, as reported by Kornmann, and attributed to the constraint imposed on the polymer chains by the silicate particles.

Wang and Pinnavaia have shown that the total solvent uptake by epoxy-silicate nanocomposites is reduced as the volume fraction of the silicate is increased, although it is unclear whether saturation was reached or whether any secondary uptake effects were observed. However, the addition of particles can increase the water uptake of epoxy polymers. For example, Lekatou et al found that increasing the volume fraction of glass beads in an epoxy matrix increased the water uptake at saturation and the rate of water uptake. This was attributed to areas of low crosslink density at the particle/matrix interface providing an easy pathway for water to enter. Evidence for water molecules clustering at the particle/matrix interface has been proposed. However, the use of silane coupling agents improves the adhesion between the particles and the matrix and may reduce the water uptake of the modified polymers. Silanes have been shown to displace water molecules, and to improve the durability of epoxy to aluminium alloy bonds. However, the effect of the alkylammonium treatment on the water uptake of polymer-silicate nanocomposites has not been systematically studied.

It does appear that the water uptake of particulate-modified polymers obeys the standard Fickian models. However, it was also observed that fracture of the water-saturated polymer was initiated at the inorganic particles, due to hydration and swelling of the particles.

Fire Resistance
The fire resistance of thermosetting fibre-reinforced composites is a critical factor, which can limit their application in areas such as civil aviation. However, polymer-silicate nanocomposites have been shown to possess improved fire resistance compared to the neat polymer and even to some conventionally fire-proofed formulations. The nanocomposite materials show a lower peak heat release rate, and in some cases a longer ignition time than the unmodified polymers. The mechanism for this improved performance is the formation of a char layer, composed of well-ordered silicate layers, on the surface of the sample which resists the applied heat.

Density
One disadvantage of using silicates is that they are relatively dense compared to the polymer. If the mechanical properties can be improved using only a small percentage of silicate, as with many polymer-silicate nanocomposites, then the density is not raised significantly. However other modifiers, such as carbon nanotubes, hollow glass spheres and POSS are less dense and the increase in density is much less significant.

Conclusions
There are many similarities between the behaviour of micro- and nanocomposites, and many of the models used to describe the properties of microcomposites appear to apply for nanocomposites. Generally properties are not a function of particle size, but high aspect ratios are beneficial. Due to the high aspect ratio of many nanoparticles, the properties of nanocomposites are better than those of microcomposites for a given volume fraction of modifier. The adhesion between the particles and the matrix is important, as for high modulus and tensile strength good adhesion is required, but for high fracture toughness imperfect adhesion may be beneficial. Polymer-silicate nanocomposite structures reduce the rate of solvent and water uptake. However, the percentage uptake at saturation may be increased due to the presence of water at the particle/matrix interface, and particle swelling may initiate premature failure. As is typical with materials selection, a balance of properties needs to be found for a given application. However, nanocomposite structures can enable materials with better overall properties to be produced.

Acknowledgements

Brief History of Smart Materials: Actuators – Examples of Where They Appear Useful

Gary Anderson, US Army Research Office, P. O. Box 12211, Research Triangle Park, NC 27709-2211, USA

A "smart" or active material is one that undergoes a change of stiffness or deformation due to the action of an external stimulus. Typical active materials are piezoelectric, electrostrictive, and magnetostricitve materials, shape memory alloys (such as nitinol: NiTi), and electro- and magneto-rheological fluids. Recently, new materials with enhanced actuation capabilities have been produced in academic laboratories. Examples include relaxor ferroelectric materials, alkaline based piezoelectric materials, and ionic polymer materials.

A "smart" or adaptive structure is a structure, typically fabricated from composite materials, that includes bonded or embedded sensors and smart material based actuators with a control system that enables the structure to respond in real time or nearly real time to external stimuli to compensate for undesired behaviour or to effect a desired response. In view of the Army's need to improve the performance of its weapon systems and fleets of rotorcraft and land vehicles, much of the research activity conducted to date has been devoted to structural vibration suppression, interior and exterior noise reduction, aeromechanical stability enhancement, gust load alleviation, structural shape (e.g., camber) change, and damage detection.

Significant progress has been made to date in suppressing structural vibrations through the introduction of active constrained layer damping treatments, a non-linear control scheme with a coupled electronic circuit, a coupled electric circuit with a resistor and a capacitor, or magnetorheological fluid dampers. In helicopter rotor blades, piezoceramic strips and piezoelectric fibre composite actuators with interdigital electrodes are used to twist the blade along its longitudinal axis to diminish vibration amplitudes and to reduce exterior noise due to blade-vortex interaction. Other techniques, including piezoceramic actuation of a trailing edge flap or programmed blowing of a directed compressed air jet to modify the aerodynamic flow, have been investigated. Pairs of piezoelectric sensors and actuators are proposed for use to detect the presence of damage in composite structures.

Numerous barriers to the advancement of adaptive structures concepts have been identified. Prominent among these is the necessity to develop enhanced or new actuators that can deliver adequate levels of force or displacement to realize the necessary degree of rotor blade twist or to damp vibrations in full scale structures. Improved actuation materials and related constitutive equations are required to be able to deal effectively with the modelling of actuators that can produce greater stroke or force. The development of these capabilities will permit adaptive structures concepts to be applied to structures that must function in the real world and to problems of critical value to the Army, such as the reduction of interior structural sound levels, electromagnetic antenna shape control, and the exterior aeroacoustics problem associated with high speed impulsive noise.

Carbon nanotube modified polymers

Milo Shaffer, Department of Materials Science & Metallurgy, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ

Nanotubes are an allotrope of carbon that have been the focus of intensive investigation over the last ten years. Experimental and theoretical results suggest that carbon nanotubes (CNT) and carbon nanofibres (CNF) hold promise as reinforcement materials for novel polymer nanocomposites, since the individual nanotubes have remarkably high mechanical properties. Due to the variation in nanotube dimensions, they may be regarded either as conjugated polymer molecules or as very fine fibres. Combinations with conventional polymer matrices are then either blends or composites; however, regardless of terminology the high interaction surface area between nanotubes and polymers means that changes in polymer morphology and properties can be significant, in addition to the direct influence of the nanotubes. Indeed, the range of nanotube properties and their interaction with polymer matrices mean that nanotube-polymer composites may be suitable for a wide range of applications.

We have investigated a range of composite systems using nanotubes and nanofibres of differing structure and diameter in a number of representative matrices. We have used broadly two approaches to composite fabrication. One is based on the use of chemical treatments to produce

nanotube solutions that can be used for direct film casting or in situ polymerisation. The other uses an intensive shear mixing protocol in conventional thermoplastic processing equipment to produce a high degree of filler dispersion. We have then fabricated macroscopic standard test samples by injection moulding or hot pressing. In all cases, the degree of dispersion can be monitored directly by electron microscopy and by analysis of the dielectric response. We have measured a range of composite properties, ranging from thermal stability, to mechanical performance, to electrochemical behaviour, depending on the matrix and its likely applications. As with conventional composites, we have found that the critical factors influencing composite performance are the crystalline quality of the nanofiller and the nature of the filler dispersion. The quality of the polymer nanotube interface can be examined using Raman spectroscopy which can indicate the degree of the load transfer between matrix and fibre. In addition, we have examined the influence of the nanoscale fillers on the resulting polymer morphologies with regard to changes in the crystallinity in the vicinity of the fillers.

4. Reports of Focus Groups

Group A	Group B
Facilitator Sjaak Elmendorp, TU Delft/Avery Dennison (NL)	*Facilitator David Porter, QINETIC (UK)*

1: Materials

1A: Evidence for Useful Properties

Modulus – double *Tensile strength* – 50% increase - Fracture toughness – 50% increase (Insufficient room for polymer chains to move in nano-composite. Small plastic zones, hence little energy dissipation) *Hardness* - double *Transparency* – excellent *Conductivity* – 10 orders of magnitude *Ballistic/impact performance* – not much evidence for good properties *Permeability* – reduced factor of 10 *Flammability* – halve heat release rate *Thermal conductivity* – Unsure, should increase significantly - Thermal expansion coefficient – reduced factor of 10 - Thermal resistance – increased HDT	- Nanocomposites/nanostructured polymers are important as a material class; simple observation of nature - For structural properties maybe little special/new about nanocomposites - For functional properties maybe whole new set of effects possible due to unexpected synergy of materials at nanoscale - Nature; nanostructures everywhere - Other nanostructured materials have clear advantages - e.g. ceramics reduce defects, allow ideal properties - Most active research has moved beyond simple structural properties - e.g. 50% modulus increase, no toughness improvement - Now looking for niche improvements in functional properties - e.g. barrier, electronic, fire retardant, templating ...

1B: Candidate Materials

- Thermoplastics more than thermosets (filling the galleries) - Fibres and platelets, rather than particles - Nanotubes - mechanical and electrical properties - Clay – barrier properties - POSS – toughness/T_g balance - Fibres made from nanotubes - strength	- Filler: not enough data yet for true selection - e.g. why specific clays; is processing easier? - Do not understand nanoscale aspects to make selection - e.g. are clay layers flexible or rigid? - Polymer: what do we want to improve? - is choice limited by processing? - do we want/need to improve properties? - are commodity polymers more important?

1C: Combination with Long Fibre Composites

- Improve compressive strength of composites by at least 50% - Class A surface finish - Cure shrinkage cracking - Dimensional stability - Dielectric properties - Improved Interlaminar shear strength	- for barrier improvement with water - conductivity - part of a hierarchical design strategy - mechanical properties doubtful improvements

1D: Manufacturing Methods

- Nano-structure management key opportunity - Short-fibre reinforced polymer manufacturing methods applicable, but same problems (orientation management, attrition) too	- synthetic fillers viable, e.g. nanotubes - natural fillers – improvements needed - composites: needs considerable development - e.g. extrusion needs optimising - e.g. self assembly not yet possible

1E: Applications

Near-term - Packaging, sports goods - barrier - Consumer goods casings - stiffness - Paints - conductivity - Cable insulation – fire retardancy *Long-term* - Halogen- and phosphorous-free fire retardants - Space-elevator (infinite breaking length, see article in Science) - Munitions and Antennas	*Near term* - modify current applications of polymers *Medium term* - use functional aspects - e.g. electrical, barrier, fire, surface abrasion *Long term* "smart" aspects of nanostructures - e.g. sensors biocompatibility; structural/functional

2: Probes

2a: What Interface and *Interphase* Properties • Identify polymer presence in galleries • Behaviour of polymer close to interface • Surface adhesion **2b: How to Probe these properties** • NMR (Interphasial mobility) • ESR. (Interphasial mobility) • Dielectric. (Interphasial mobility) • Nanotube-tipped AFM – local stiffness, conductivity • Nano-fibre pullout in SEM - interfacial strength • High resolution TEM and AFM • X-ray scattering **2c: New Tools** • Non-destructive interface strength • On-line analysis to identify structure formation • 3-D electron holography to visualize structural details • Positron annihilation for density profiles in the galleries	• a), b), c)Perhaps should consider probes as a whole • not just interfaces: • what do we want to probe • levels of structure: general probe of overall nanostructure • microscopy + scattering • radial distribution function • Interfaces as example (speculative discussion): • surface forces……polymer configuration at interfaces • AFM with attached molecules: bioanalysis • Raman peak shifts • luminesence:chromophores with decay lifetimes

3: Fundamental Understanding and Modelling

3a: Significance of Scale • Relative to processing equipment (processability at high aspect ratio) • Relative to event, e.g. plastic zone (ballistic) • Relative to wavelength of light (transparency) • Relative to long-range forces (density profiles, aggregation)	• Must differentiate between understanding and modelling
3b: Models • Inputs=>model=>methods=>number crunching=>outputs • Can model crystalline materials (known microstructure but e.g. amorphous state of polymers as yet intractable • Ability to build atomic-scale models • Prediction of macro-scale properties from nano-scale models quite feasible when structural information is available	• we do not have enough fundamental understanding • lack of data from controlled scaling experiments
3c: Computational Facilities • Very dependent on method used • Lack of facilities or computer power is not main problem for the key current needs • Development of models and methods more critical	• modelling needs to be coupled to this experimental programme
3d: Calculation of Interface Properties • Energetics and stress transfer properties from fundamentals relatively easy, at least a relative ranking of material combinations should be predictable • Longer-range properties much more challenging	• note modelling not same as molecular simulations • need proactive modelling suggestions to test by experiment

4: R&D Planning

- Nanocomposites still require fundamental work - Should be targeted to functional materials as they may benefit from the nano-composites concept more than structural materials - Nanocomposites not necessarily structural in own right, but can be used to add value, complementing existing technology - Hierarchy of length scales implies need for Multi-scale modelling **Capabilities Needed** - Quantitative analysis of structure (aspect ratio, dispersion etc.) - Surface chemistry - Ability to scale up modifiers in high volume and low cost **Other Miscellaneous Thoughts** - Interface properties - Multifunctionality - Note: Macroscopic may not be most applicable properties - Need models to help focus research - Results interesting, but not order of magnitude improvements - Insufficient room for polymer chains to move in nanocomposite. Small plastic zones, hence little energy dissipation - Orientation effects. Limited ability to 'engineer' properties. Need new manufacturing processes - Value-added properties – e.g. conductivity. Carbon nanotubes used in paint by GM - Nanocomposites not very promising for structural applications on their own - Biomimetics	- Main issue: is R&D effort coordinated? - US seems OK generally - UK some problems on general nanocomposites - e.g. Interdisciplinary Research Centre set up - mechanisms needed to keep all parties in contact - General question: need to start: will get cheaper, yes, but may lead elsewhere - need to link to industry: who will make our nanocomposites?

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APPENDIX A - List of Participants

Max Alexander	Air Force Research Laboratory Polymer Branch Wright-Patterson AFB Dayton, OH 45433-7750, USA
Gary Anderson	US Army Research Office P. O. Box 12211 Research Triangle Park NC 27709-2211, USA
Richard Allington	Defence Science and Technology Laboratory Porton Down Salisbury Wiltshire SP4 0JQ
Rick Beyer	Army Research Laboratory Weapons and Materials Research Directorate Building 4600, AMSRL-WM-M Aberdeen Proving Ground, MD 21005-5069, USA
Khershed Cooper	Naval Research Laboratory Materials Science and Technology Division, Code 6324 4555 Overlook Ave. SW, Washington, DC 20375, USA
John Ebdon	Department of Mechanical Engineering University of Sheffield Mappin Street Sheffield S1 3JD
Sjaak Elmendorp	Laboratory of Chemical Engineering Technical University of Delft Julianalaan 136 2628 BL Delft, Netherlands
Steve Fossey	Materials Science Team Natick Soldier Center Kansas Street Natick, MA 01760-5020, USA
Fengge Gao	Department of Mechanical and Manufacturing Engineering The Nottingham Trent University Burton Street Nottingham NG1 4BU
Graham Gray	University of Surrey Department of Chemistry School of Physics and Chemistry Guildford GU2 7XH
Gary Hagnauer	Army Research Laboratory Weapons and Materials Research Directorate Building 4600, AMSRL-WM-M Aberdeen Proving Ground, MD 21005-5069, USA
Noureddin Moussaif	Katholieke Universiteit Leuven Department of Chemistry Laboratory of Macromolecular Structural Chemistry (MSC) Celestijnenlaan, 200 F, 3001 Heverlee, Belgium
Ivana Partridge	Reader in Polymer Composites Advanced Materials Department, SIMS 61 Cranfield University Bedfordshire MK43 0AL
David Porter	Structural Materials Centre DERA Farnborough A7/2008 Farnborough GU14 0LX

Chris Rudd	Professor of Mechanical Engineering School MMMEM University of Nottingham University Park, Nottingham NG7 2RD
Milo Shaffer	Department of Materials Science & Metallurgy University of Cambridge Pembroke Street Cambridge CB2 3QZ
Robert Shaw	Chemistry and Materials Science European Research Office Edison House, 223 Old Marylebone Road London NW1 5TH
Ambrose Taylor	Department of Mechanical Engineering Imperial College of Science, Technology and Medicine Exhibition Road London SW7 2BX
Geoff Tomlinson	Department of Mechanical Engineering University of Sheffield Mappin Street Sheffield S1 3JD
John Zavada	Chemistry and Materials Science European Research Office Edison House, 223 Old Marylebone Road London NW1 5TH

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APPENDIX B - Participant Biographies

Max D Alexander Jr

Air Force Research Laboratory, Polymer Branch, Wright-Patterson AFB, Dayton, OH 45433-7750, USA

Max Alexander is currently leader for the Conductive Elastomer research effort in the Polymer Core technology Area at the US Air Force's Materials and Manufacturing Directorate at Wright-Patterson AFB, Dayton OH, USA. His research group focuses on understanding processing – structure – property relationships of polymeric based nanostructured materials for military applications including satellites, aircraft and ground structures. Recently his work has focused on the study of uniformly dispersed carbon nanotube-polymer composites and the performance advantages of these systems. He holds Master of Science Degrees in both Chemistry and Physics and is preparing to defend his Ph.D. dissertation in field of Materials Science and Engineering. He currently holds 3 patents and has published in over 30 journal articles.

Richard Allington

Platform Systems & Technology Department, 1052, A2 Building, Defence Science and Technology Laboratory, Ively Road, Farnborough, Hampshire GU14 0LX

Technical Focus for Polymeric and Adhesive Materials within the Platform Systems and Technology Department at the Defence Science and Technology Laboratory (DSTL).   I am the initial DSTL point of contact for the UK Ministry of Defence for polymer and adhesive issues covering air, land and sea platforms.   My work encompasses research projects focussing on structural adhesive bonding, smart adhesives, dendritic polymers and polymeric nanocomposites.   I represent the UK as National Leader on the five nations TTCP panel covering Polymeric, Adhesive and Sealant Materials (MAT-TP-6).

Gary Anderson

US Army Research Office, P. O. Box 12211, Research Triangle Park, NC 27709-2211, USA

Dr. Anderson is responsible for the management of the fundamental research program in Structures and Dynamics. The main emphasis of the program is helicopter dynamics, the dynamics of smart structures, dynamic response of composite materials, structural vibrations and stability, and the dynamics and control of deformable mechanisms. Other areas of relevance of this program occur in land vehicle, robotic, mechanism, and weapon system dynamics. Duties consist of technical evaluations of university research proposals; organization of technical workshops in helicopter rotor blade dynamics, non-linear vibrations and stability, smart structures, robot dynamics; performance of quality assessments of research programs at various Army laboratories; and surveillance of research trends in the technical areas named above.

Senior Scientist, Mechatronics Group, Institut CERAC S.A., Ecublens, Switzerland (1975-1985)
Duties and responsibilities included project coordination for the Mechatronics Section (seven engineers and technicians), participation in scientific and industrial symposia, visiting university and industrial laboratories in Europe and North America, interaction with the parent companies (the Atlas Copco Group in Sweden and Belgium), and the development and execution of fundamental research projects. Accomplishments included the surveying of trends in manufacturing methods and robotics; completion of several technical projects concerned with vibration and stability of elastic structures, control of motion of deformable bodies, the dynamics of industrial manipulators and hand held tools,

publication of technical papers in archival journals, and the development of mathematical methods for the numerical inversion of Laplace transforms and the acceleration of the rate of convergence of infinite series.

Applied Mathematics and Mechanics Branch, US Army Bénet Weapons Laboratory, Watervliet Arsenal, Watervliet, New York (1969-1975)
Duties included the coordination of an aircraft structures program (5 scientists), interaction with the sponsoring agency, participation in scientific symposia, and the development and execution of fundamental research projects. Numerous technical reports were written and several scientific papers were published in international technical journals. Research dealt with the solution of problems in the theory of non-conservative stability, development of effective mathematical methods of numerical approximation, determination of the dynamic response of elastic structures, and the prediction of the dynamic characteristics of laminated and fibre reinforced composite structures, and the development of solution techniques for non-linear oscillation problems.

Professor, Department of Mechanics, Rensselaer Polytechnic Institute, Troy, New York (1965-1969)
Duties included the teaching of undergraduate and graduate courses in rigid body mechanics, continuum mechanics, plate theory, and shell theory; supervision of doctoral theses; and development and execution of fundamental research projects. Nine technical papers were published in archival journals. These papers were concerned with applications of finite integral transforms to boundary value problems arising in the theory of structures.

Memberships (past and present):
American Institute for Aeronautics and Astronautics
American Helicopter Society
Society for Industrial and Applied Mathematics
Acoustical Society of America
Associazione Italiana di Meccanica Teorica ed Applicata
Associazione Italiana di Robotica Industriale

Rick Beyer

Army Research Laboratory, Weapons and Materials Research Directorate, Building 4600, AMSRL-WM-M, Aberdeen Proving Ground, MD 21005-5069, USA

Research Interests
Polymer morphological behaviour, thermodynamics, and physics
Polymer-layered silicate nanocomposite behaviour and use
Small-angle X-ray and neutron scattering techniques and electron microscopy for structural characterization on the sub-micron scale of polymeric materials

Education
Ph.D., POLYMER SCIENCE & ENGINEERING   *University of Massachusetts Amherst*, 1999
Dissertation entitled "The Morphological Behaviour of Miktoarm Star and Multiple-Graft Block Copolymers"
Thesis advisor: Prof. Samuel P. Gido
M.S., POLYMER SCIENCE & ENGINEERING   *University of Massachusetts Amherst*, 1999
B.S., MATERIALS SCIENCE & ENGINEERING *North Carolina State University*, 1993
Summa cum laude, mathematics minor

Awards and Activities
Reviewer for *Macromolecules*
American Society for Engineering Education Post-doctoral Research Fellowship, 1999-2001
University of Massachusetts Amherst Graduate Fellowship, 1994-1995
Member, Phi Kappa Phi, Academic Honor Society
Mercury 7 Foundation (Astronaut Scholarship Foundation) Scholarship, 1992-1993
Member of the Division of High Polymer Physics of the American Physical Society

Member of the American Chemical Society
Member of the Materials Research Society
Attended the NIST Summer School on Neutron Small-Angle Scattering and Reflectivity from Submicron Structures

Technical Skills
X-ray and neutron scattering techniques for polymeric materials
Instrument scientist for Bruker Hi-Star WAXS/SAXS system, Rigaku Ultrax18 rotating anode X-ray generator
Polymer microscopy: TEM, but also SEM, FESEM, and optical; ultracryomicrotomy

Professional Experience
1999-present: *Post-doctoral Research Fellow, US Army Research Laboratory, Polymers Research Branch, Aberdeen Proving Grounds, Maryland*
Investigating miscibility, thermodynamics, and morphological behaviour of model polymer-layered silicate composites
Investigating the intercalation and conformational behaviour of PEO-b-PS copolymers in montmorillonite and hectorite
Examined layered silicate clay minerals as reinforcing agents in energetic binder materials
Maintained and improved existing SAXS facilities

1994-1999: *Research Assistant, University of Massachusetts Amherst, Department of Polymer Science & Engineering*
Correlated architecture, thermodynamic-structure relationships, and morphology for regular and random multiple-graft block copolymers, A_2B_2, A_8B_8, and A_5B star block copolymers
Developed correlations between mechanical properties and morphology of blown PE
Quantified lamellar thickness distributions in LLDPE for correlation with NMR measurements
Laboratory instructor, 3 semesters

Kershed P Cooper

Naval Research Laboratory, Materials Science and Technology Division, Code 6324, 4555 Overlook Ave., SW, Washington, DC 20375, USA

Experience
Program Officer Detailee (1998-present), Manufacturing Science & Technology Division, Office of Naval Research (ONR), Arlington, VA.
Metallurgist (1990-present), Materials Science & Technology Division, Naval Research Laboratory (NRL), Washington, DC.
Supervisor (1984-1990), Materials Science Group, Geo-Centers, Inc., Fort Washington, MD. (NRL On-site).
Research Scientist (1982-1984), Olin Metals Research Laboratory, New Haven, CT.

Education
Ph.D. (MetE), 1982, University of Wisconsin, Madison, WI. Minor: Business Marketing.
MS (MetE), 1977, University of Wisconsin, Madison, WI.
B.Tech. (MetE), 1975, Indian Institute of Technology, Bombay, India.

Scientific and Technological Interests
Explore and promote advanced materials development, from nanomaterials to bulk materials.
Explore novel fabrication/manufacturing technologies such as rapid prototyping, layered manufacturing & solid freeform fabrication.
R&D of materials and processing for structural, device, power, energy, sensor, and other applications.

Presentations
Total 51. -- Invited 24. Contributed 27.

Publications
Total 60. -- Book 1. Book Chapter 1. Journal 21, Proceedings 27. Reports 8. Reviews 2.

Invited Panellist
Panel on "Rapid Prototyping, Rapid Tooling and Solid Freeform fabrication in the New Millennium", Manufacturing Engineering Division, The 2000 ASME International Mechanical Engineering Congress & Exposition, Orlando, FL, November 5-10, 2000.
Workshop on "NanoTechnology Applications for Aerospace Structures Health Sensing", USAF Research Laboratory Space Vehicles Directorate, Kirtland AFB, NM, May 30-31, 2001.

Program Presentations
K. P. Cooper for R. Wachter and P. Quinn, "ONR 31-05: Information Integrity and Privacy", Dual-Use Science & Technology Program (DUS&T) Investment Strategy Conference, New Orleans, LA, February 3, 2000.
K. P. Cooper, K. Bussmann, G. Hubler and M. Pederson, "NanoMaterials Research at NRL", NASA/NRL Meeting on NanoTechnology, NRL, August 17, 2000.

Honor Societies
Sigma Xi (Scientific Research); Alpha Sigma Mu (Metallurgy).

Awards
George Kimball Burgess Memorial Award, ASM International, Washington, DC Chapter, 2001.
Best Paper Award, International Metallographic Society, 1998.
Science-as-Art Award, NRL, 1998.
Invention Award, NRL, 1996.
Alan Berman Annual Research Publication Award, NRL, 1991.
Past Chairman Chapter Award, ASM Int., Washington, DC Chapter, 1995.
Yearbook Dedication, ASM Int., Washington, DC Chapter, 1994-95,
Outstanding Young Member Award, ASM Int., Washington, DC Chapter, 1988-89.

Professional Affiliations
ASM International; The Minerals, Metals, Materials Society-AIME (TMS). Member, TMS Solidification Committee, 1985-present; TMS Powder Materials Committee, 1997-present.

Offices Held
JOM Advisor, TMS, Solidification Committee, 2000-present.
JOM Advisor, TMS, Powder Materials Committee, 1998-2000.
Member, Chapter Council, ASM International, 1994-97.
Advisor, 1995-present; Past Chairman, 1994-1995; Chairman, 1993-1994; Treasurer, 1991-1993; Arrangements Committee Chairman, 1987-1991, Washington, DC Chapter of ASM International.

Technical Activities
Member, Navy Working Group on Nanoscience and Nanotechnology (NWGN) for the NNI, 2000-present.
Member and Chair, Unsolicited Proposal Review Panel, Division of Design, Manufacture and Industrial Innovation, NSF, Arlington, VA, December 5, 2000.
Graduate student advisor, US Naval Academy, "Copper Electrode Degradation Due to the Resistance Welding of Aluminum", 1998-99.
Participant, Reviews, Consortia, Workshops and Meetings related to Program Officer Detailee position.
Member, Metals and Alloys Review Panel, Microgravity Science and Applications Division, NASA, Washington, DC, May 28-29, 1992, December 20-21, 1993, October 9-11, 1995, May 28-30, 1997.
Proposal Reviewer, Materials Processing for Heavy Manufacturing, ATP, NIST, Gaithersburg, MD,
Reviewer for *Thin Solid Films, Metallurgical Transactions, Int. Journal of Powder Metallurgy, Materials Science & Engineering, Journal of Applied Physics.*

Professional Society Activities

Session Chair, "Rapid Prototyping, Rapid Tooling and Solid Freeform Fabrication in the New Millennium", ASME International Mechanical Engineering Congress & Exposition, Orlando, FL, November 5-10, 2000.

Judge, "Manufacturing Engineering Division Student Manufacturing Design Competition", The 2000 ASME International Mechanical Engineering Congress & Exposition, Orlando, FL, November 5-10, 2000.

Symposium Organizer, "Liquid Metal Atomization: Fundamentals and Practice", TMS Annual Meeting, Nashville, TN, March 12-16, 2000.

JOM Advisor, Manufacturing Lightweight Materials, "The Powder Processing of Lightweight Materials", JOM, vol. 52, no. 5, May 2000.

JOM Advisor, 21st. Century Technologies, "Near Net-Shape P/M", JOM, vol. 51, no. 7, July 1999.

John Ebdon

Professor of Polymer Chemistry and Director of the Polymer Centre, University of Sheffield, Mappin Street, Sheffield S1 3JD

My main research interests are in chemical modification of polymers to improve flame retardance and in synthesis of telechelic (terminally functional) polymers useful as building blocks for the construction of more complex materials. I have much past experience also in radical polymerisation, NMR analysis of polymers, and chemistry of thermosetting resins. I have developed a recent interest in some polymer/clay nanocomposites as potential routes to strong fibres and as components of flame retarded thermoplastics.

I currently have 140 research publications.

Currently, I am Chairman of the Pure and Applied Macromolecular Chemistry Group (Macro Group UK) of the Royal Society of Chemistry and the Society of Chemical Industry.

Sjaak Elmendorp

Laboratory of Chemical Engineering, Technical University of Delft, Julianalaan 136, 2628 BL Delft, Netherlands

J.J. (Sjaak) Elmendorp was born 19-8-1958 in Vlaardingen, The Netherlands, and graduated there from Atheneum-B. He holds a masters in Physics from the Delft University of Technology and a PhD in Chemical Technology on "A study on Polymer Blending Microrheology", a study sponsored by DSM (mentor H.E.H. Meijer)

From 1-11-1985 through 31-12-1993 he has been employed by the Koninklijke/Shell Laboratorium, Amsterdam, one year of which (1-7-1989 through 30-6-1990) as an "Exchange Scientist" at the Westhollow Research Center of the Shell Development Company in Houston, Texas. Initially, he has conducted a project on Dynamical Wetting phenomena in multiphase, thermoplastic polymer systems. Thereafter he was responsible for coordinating corporate research in support of a number of Shell subsidiaries involved in downstream activities.

          After returning to KSLA he was put in charge of a research group developing epoxy resin systems for automotive composites and developed excellent working relationships with the key car manufacturers. In addition, the coordination of development and market introduction activities worldwide, were his responsibility.

Towards the end of 1993 two career opportunities opened up, one of which as full time professor of Polymer Technology at the University of Twente, an opportunity that has not been pursued as the envisaged areas of research and Elmendorp's personal aspirations did not appear to coincide.

In 1-1-1994 he assumed the position of R&D Director for the European Roll Label division of Fasson, part of the Avery-Dennison group of companies. In this position he headed up the 32 strong European R&D centre in Leiden, The Netherlands and coordinates a number of global product and business development projects. These are geared to rejuvenating the companies portfolio of self adhesive

products and include the developments of adhesive and silicone systems, paper and filmic front material developments and process developments.

Per 1st November 1997, he was promoted to position of Vice-President Product Technology and Innovation for the Fasson Roll North America and Fasson Roll Europe divisions of Avery Dennison, based in Concord, Ohio, USA.

He has recently been appointed Professor of Polymer Engineering, at the University of Delft, The Netherlands, at the Polymer Materials and Engineering group of the faculty of Materials Science, where his research field is Polymer Blends and Composites

He holds 21 publications in International Journals, is married and has two children.

Steve Fossey

Materials Science Team, Natick Soldier Center, Kansas Street, Natick, MA 01760-5020, USA

Education
PhD Polymer Science/ Plastics Engineering (University of Massachusetts Lowell)
MS/ BS Chemical Engineering (University of Massachusetts Lowell)

Experience
Presently: Materials Research Engineer, Science and Technology Directorate, Natick Soldier Center
US Army Soldier, Biological, and Chemical Command
1989-91 Visiting Scientist, Cornell University, Department of Chemistry

Fengge Gao

Department of Mechanical and Manufacturing Engineering, The Nottingham Trent University, Burton Street, Nottingham NG1 4BU

Dr Gao is a Senior Lecturer and the Manager of the Polymer Engineering Centre at the Nottingham Trent University. He has nearly 20 years of research experience in fibres, composites, polymers and damage mechanics subsequently carried out at Loughborough University, University of Surrey, University of Salford and The Nottingham Trent University. He is now leading a team at the Polymer Engineering Centre working on the development of nano-structured polymers with great potential for commercialisation using traditional polymer processing equipment. Recently he has been awarded more than £0.7M external fund from world leading industries in USA, Germany and the UK to support his research in clay, graphite and metal based polymer nanocomposites.

Graham Gray

University of Surrey, Department of Chemistry, School of Physics and Chemistry, Guildford, Surrey GU2 7XH

Graham Gray first became interested in polymer and materials chemistry during his undergraduate degree at the University of Kent. He subsequently stayed on to investigate novel silicon based polymers for his PhD in collaboration with Dow Corning (UK).

He is currently a postdoctoral fellow investigating organic-inorganic sol-gel hybrids at the University of Surrey. His research is mainly concerned with the potential of lyotropic ionene polymers to function as templates and so control the synthesis of mesoporous silicas.

Gary Hagnauer

Army Research Laboratory, Weapons and Materials Research Directorate, Building 4600, AMSRL-WM-M, Aberdeen Proving Ground, MD 21005-5069, USA

Gary Hagnauer graduated from Southern Illinois University with a B.A. (1965) in chemistry, physics and mathematics and received an M.S. (1967) and Ph.D. (1970) in physical chemistry from the University of Iowa. He began his professional career as a research chemist in 1969 at the Army Materials and Mechanics Research Center in Watertown, MA and advanced to an Army Senior Research Scientist (ST) position in 1990. He is now located at the Army's Rodman Materials Research Building at Aberdeen Proving Ground, MD.

His research interests include the synthesis and characterization of novel polymer materials, polymer structure-property studies, and the testing and evaluation of advanced polymers and composite materials. He is noted for his research on polymerisation kinetics and mechanisms, on developing polymer and composite materials chemical/physical characterization techniques, and promoting defence/industry implementation of composites and novel inorganic, dendritic/hyperbranched polymers, nanomaterials technology. He oversees ARL's Weapons Materials Division's 6.1 Research and extramural University Materials Center of Excellence Program; leads the Polymer Research Team for Polymer Films and Interface Science; serves as the Army's Small Business Innovation Research (SBIR) Technology Area Chief for Advanced Materials and Manufacturing; coordinates technical programs with the Army Research Office and Natick Soldier Center; and represents the Army on the Joint Services Basic Research Scientific Planning Group (Reliance) in Materials Science. He has served as the U.S. National leader and past Chairman and Secretary for several International DoD Technical Cooperation Program TTCP Panels and as Chairman for the joint government/ industry Composite Materials Handbook (MIL HDBK-17).

Dr. Hagnauer is a member of the American Chemical Society, the Society of Plastics Engineers, the Materials Research Society, the American Society of Testing and Materials (ASTM) and Sigma Xi. He has served as Chairman of ASTM Task Groups, Trustee of the American Plastics Institute and Army/DOD representative on various government, industry and academic panels. He received the AMMRC Director's Award (1975), the Army R&D Achievement Award (1978), TTCP Achievement Awards (1985 and 1986), the Commander's Award for Civilian Service (1993), the ASTM Award of Recognition (1993), the TTCP Meritorious Service Award (1995), plus a number of Commendations and Performance Awards.

Noureddin Moussaif

Katholieke Universiteit Leuven, Department of Chemistry, Laboratory of Macromolecular Structural Chemistry (MSC), Celestijnenlaan, 200 F, 3001 Heverlee, Belgium

Education
1999: Ph.D. in Polymer Chemistry - Center for Education and Research on Macromolecules, University of Liege, Belgium.
1993: Master degree (M.Sc) in Polymer Chemistry - University of Liege, Belgium.

Research Interests
Research on nanocomposite materials based on thermoplastic polymers and layered silicates.
Polymer-polymer miscibility.
Multicomponent and multifunctional polymer and polymer / nonpolymer (filler) systems: morphology generation, interface characterization, interfacial chemical and physical modification, structure-property relationships.
Bulk and surface analysis of polymer and composite materials.

Ivana Partridge

Reader in Polymer Composites, Advanced Materials Department, SIMS 61, Cranfield University, Bedfordshire MK43 0AL

Position: READER in Polymer Composites at Cranfield University, UK
Date of Appointment: October 2000
Qualifications: *Academic*
                BA Natural Sciences (Physics), Cambridge 1975; MA, Cambridge 1978; PhD, Cranfield 1984
                Professional
                MIM

Recent Research Topics
Dielectric cure monitoring (EPSRC, EC)
Modelling epoxy cure (BAe, ShortBrothers, GKN)
Equivalent circuit models (The Leverhulme Trust)
Heat transfer aspects of RTM (EC Marie Curie TMR Fellowship)
Delamination in Z-pinned composites (DTI)
Cure induced shrinkage and residual stresses (Audi Foundation)

Career
Reader in Polymer Composites 2000 -
Senior Lecturer in Advanced Materials 1993 - 2000
Lecturer 1985-93
Research Officer 1979-85
Industrial Research in Biophysics 1975 - 1979
Other relevant information
Chair of EPSRC Engineering Programme Network 'CURENET'
(http://www.cranfield.ac.uk/sims/curenet)
Immediate past -Chair of the 'Applied Polymer Science Committee' of the Institute of Materials, current member of the Composites Division Board
Editorial board member of RAPRA journal 'Polymers and Polymer Composites'.
VAMAS Technical Working Area 4 'Multiphase Polymers' -
Represented UK 1985 - 1995, Chair of TWA4 1992 - 1995

David Porter

Structural Materials Centre, DERA Farnborough A7/2008, Farnborough GU14 0LX

Dr. David Porter is a Research Fellow at QinetiQ (formally DERA) in Farnborough working on Materials Modelling, with particular emphasis on the relationship between molecular structure and bulk physical properties. He is recognised internationally as an expert in the modelling of polymers and is the author of an important and highly innovative book on the subject: *Group Interaction Modelling of Polymer Properties*, Marcel Dekker, New York, 1995. Dr. Porter gained his experience working from 1979 to 1995 in the commercial research laboratories of Dow Chemical in Switzerland, The Netherlands and the USA. He joined DERA in 1995 to establish a materials modelling capability across a wide range of material types and application technologies.   His modelling uses molecular, nano- and micron-scale detail of the material structure within a hierarchical framework to predict nonlinear viscoelastic properties of materials for applications as diverse as accident simulation, muscular skeletal injury (such as stress fracture), adhesives, vibrational damping, lubrication, ceramic and polymeric actuator materials, and engineering composites.

Chris Rudd

Professor of Mechanical Engineering, School of Mechanical, Materials, Manufacturing Engineering and Management, University of Nottingham, University Park, Nottingham   NG7 2RD

Chris Rudd is Professor of Mechanical Engineering and Deputy Head of the School of Mechanical, Materials, Manufacturing Engineering and Management at University of Nottingham. His research interests include polymer composites, lightweight vehicle structures and materials processing. He leads a 25-strong research group examining design, manufacturing and performance issues with a strong automotive bias. He has published more than 150 papers and holds several patents. The Nottingham group has provided technical support for the introduction of several new applications in production vehicles for Ford, ranging from Transit to Aston Martin. Chris spent much of 1999 in North America under an Engineering Foresight Award to study trends in lightweight vehicle design and construction. He is a Fellow of Institution of Mechanical Engineers and of the Institute of Materials. He chairs the Institute of Materials Composites Division and Composites Foresight Steering group.

Milo Shaffer

Department of Materials Science & Metallurgy, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ

Milo Shaffer is a research fellow at Trinity College, Cambridge, working in the Department of Materials Science. He is intimately involved in running the growing nanotube team in conjunction with Prof. Alan Windle's polymer research group. He has considerable experience of manipulation, dispersion and characterisation of carbon nanomaterials. He has developed and studied a number of nanotube composite systems, including both engineering and conducting polymer matrices. Current interests include nanotube synthesis, chemistry, and their use as polymer modifiers. He has also spent time working as materials technology consultant in the areas of new technology development and exploitation.

Robert Shaw

Chemistry and Materials Science, European Research Office, Edison House, 223 Old Marylebone Road, London NW1 5TH

Before coming to ARL-ERO, Dr. Shaw was the Associate Director for Chemistry in the Physical Sciences Directorate of the US Army Research Office in Research Triangle Park, NC.   He will return to ARO in the summer of 2002. While at ERO, he is looking for people with special expertise in modelling and developing strong, light composite materials and exploring the possible role of nanostructures in these materials. His other areas of interest are compact electric power (especially fuel cells), defence against chemical/biological threats, destruction of military toxic materials, and energetic materials.
Dr. Shaw has his degree in Physical Chemistry from the University of Washington. His past research includes nuclear reactions and scattering, thermodynamics, photoelectron and Auger spectroscopy, and measurements of trace gases and aerosol particles.

Ambrose Taylor

Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, Exhibition Road, London SW7 2BX

1990 - 1993   Degree in Mechanical Engineering at the University of Bristol.
Final year project to design and build an arthrograph to measure pre- and post-operative stiffness of finger joints.

1993 - 1997   PhD at Imperial College of Science, Technology and Medicine, London.
Research into the impact and durability performance of rubber-toughened structural epoxy adhesives. Prediction of lifetime of bonded joints and components in fatigue using fracture mechanics data and finite element modelling. Correlation between impact test methods.

1997 - 2000   Research associate at Imperial College of Science, Technology and Medicine.
Research to develop tough, high-temperature resistant adhesive and composite materials. Use of high-temperature thermoplastics and inorganic tougheners including particles, mats and fibres. Investigation of formulations for high dimensional stability.

1999   Awarded Post-Doctoral Research Fellowship by the Royal Academy of Engineering.

2000   Royal Academy of Engineering post-doctoral research fellow at Imperial College of Science, Technology and Medicine.
Research into the toughening of high temperature and fire-resistant cyanate-ester polymers by the formation of organic/inorganic hybrids. Investigation into the barrier properties of inorganic particles in thermosets.

Geoff Tomlinson

Department of Mechanical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD

Current Posts
Pro-Vice Chancellor for External Affairs
Director, Division of Aerospace Engineering
Director of the Rolls-Royce UTC in Materials Damping Technologies

Research Achievements
Awarded a DSc by the University of Manchester (2001)
Awarded a Rolls-Royce University Technology Centre in Materials Technologies (1998)
Initiated the EPSRC Smart Technologies Programmes (1997)
Stimulated research (nationally and internationally) into applied nonlinear structural dynamics

Current Research Topics
Passive and Active Material Damping Technologies
Smart/Adaptive Structures and Materials
Structural Health Monitoring
Nonlinear Structural Dynamics

Professional Qualifications and Activities
Chartered Engineer
Fellow of the Royal Academy of Engineering
Fellow of the Institute of Mechanical Engineers
Fellow of the Royal Aeronautical Society
Fellow of the Royal Society of Arts
EPSRC College Member
Member of the National Advisory Committee on Aerospace Structures and Materials
Member of the EPSRC Basic Technologies Strategy Advisory Committee
Chairman of the Royal Aeronautical Society Committee on Structures and Materials
Vice Chairman of the Non-linear Oscillations International Committee of IFToMM

Editorial Boards and	Journal of Smart Materials and Structures
Journal Referee	Journal Mechanical Systems and Signal Processing
	Journal of Non-linear Dynamics
	Journal of Vibration and Control
	Journal of Sound and Vibration
	Proc. IMechE
	ASME (Vibration & Acoustics)
	Journal of Mechanical Engineering Science
Book Review Editor	IMechE (Pt C, Journal of Mechanical Engineering Science)
Book Reviewer	Academic Press, Macmillan Press Ltd
PhD External Examiner	Aston, Bath, Cambridge, City, Dundee, Heriot-Watt, Imperial College of Science, Technology and Medicine, Liverpool, Manchester, Nottingham, Salford, Sheffield, Southampton, Technion (Israel), Texas A & M (USA), Illinois (USA), Institute Superieur Materiaux et de la Construction Mecanique (France), New South Wales (Australia), Hong Kong.
Undergraduate Course External Examiner	Strathclyde, (current), Nottingham, Liverpool, Bath, Dundee, City University.
Consultant to	EPSRC, MoD, BAE Systems, Rolls-Royce plc, Fiat(CRF), Los Alamos Laboratories (New Mexico), USAF, Rolls-Royce Marine, HP, Rieter Automotive, IWT (Flanders Region, Brussels).

University Committees
Member of the Senior Management Group
Member of the Academic Development Committee
Member of the Research Strategy Group and the Research Committee
Chair of the Service Quality Team for Research Services
Member of Senate
Chair of the European Research Task Force
Member of the International Advisory Group

John M. Zavada

Chemistry and Materials Science, European Research Office, Edison House, 223 Old Marylebone Road, London NW1 5TH

John M. Zavada is the Director of the European Research Office of the U.S. Army Research Laboratory and also serves as Chief of the Electronics & Physics Branch. Previously, he managed a research program in optoelectronics at the U.S. Army Research Office in Durham, NC. He earned his BA from the Catholic University of America and his MS and PhD degrees in physics from New York University. Later he worked as a research physicist at Army laboratories in Philadelphia, PA, and at Picatinny, NJ. Dr. Zavada has authored more than 100 papers in the areas of scattering of light from rough surfaces, ion implantation, optical characterization of semiconductors, and hydrogen and rare earth impurities in materials. He has served on numerous advisory panels, including the Joint Services Electronics Program and the Advisory Group on Electronics, and on program committees for international conferences in solid state physics and electronics. He has held adjunct academic positions at Drexel University, North Carolina State University, and the Imperial College of Science and Technology. He is a member of the American Physical Society, the Materials Research Society, and is a Fellow of the Optical Society of America.

APPENDIX C.

Evaluations

A questionnaire was given to participants to complete at the end of the Workshop, and the following details were collated:

- Organisation of the Workshop was considered Good (the highest category) - 100%
- The content of the Workshop was considered Good (the highest category) - 95%

Parts found to be most useful to participants were the discussion session after each presentation. The presentations by participants were found to be interesting, and groups on the final day discussed their findings, which gave real statistics on nanocomposites and thoughts on future directions.

Participants listed a wide range of topics which they would have liked to see included in the Workshop. These included such items as POSS, Sol-gel hybrids, flammability and barrier, current industrial state of art/future outlook, design and preparation of nanocomposite material, nano-devices/nano-sensors in composite structures. One participant would have liked an overview of the history of the field together with the status of the current activity. More expertise in modelling was also suggested. Very high particulate content materials may have been interesting to participants and biological systems could have been emphasised more.

It was felt that not all of the military presentations were sufficiently focussed on nanocomposites or the overtly stated workshop objectives. Participant abstracts, on the whole, could have been more informative.

Overall, participants considered the Workshop to have been very useful and, in view of the catastrophic events of September 11th 2001, was conducted in a very professional manner. It was suggested that each of the participants should specifically address each of the workshop goals during their presentation, possibly by asking presenters to append two slides at the end of their presentation. Shorter presentations to allow more time for discussions was also suggested. A comment was noted that the possibility of involving others, such as DTI, EPSRC, industry (if relevant and willing), at a future workshop should be considered. Participants considered the event, useful and encouraging to think about challenging issues, and expressed the hope that a similar event could be held in the future.